(54) The fuel supply for a gas turbine regulated in accordance with a synthesized turbine inlet temperature

(57) A method and apparatus are disclosed for protecting gas turbines (two- and three-shaft) from damage or destruction during dangerous transients. In this situation, fuel flow must be reduced, as needed, to keep the exhaust gas temperature below a maximum limit, thereby avoiding damage to blading in the turbine's first-stage. The dynamic action of the temperature downstream of the combustion chamber may be estimated and then used to correct the temperature measured by thermocouples. For this approach, the turbine is instrumented with an inlet pressure transmitter and an outlet temperature transmitter. The method dynamically estimates temperatures downstream of the combustion chamber and reduces the fuel flow rate if the estimated temperature approaches the temperature limit. Existing thermocouple measurements (EGT) are used as well as the pressure of air exiting the compressor (CDP) upstream of the combustion chamber. By employing a first-order lag and a steady-state gain, the measured CDP is used to predict a "correction" EGT signal which is then added to the measured EGT, resulting in a corrected EGT. Once the corrected EGT has been calculated, its first time-derivative is used to adjust the safety margin between a maximum allowable limit temperature and a lower predetermined temperature set point.

Fig. 1

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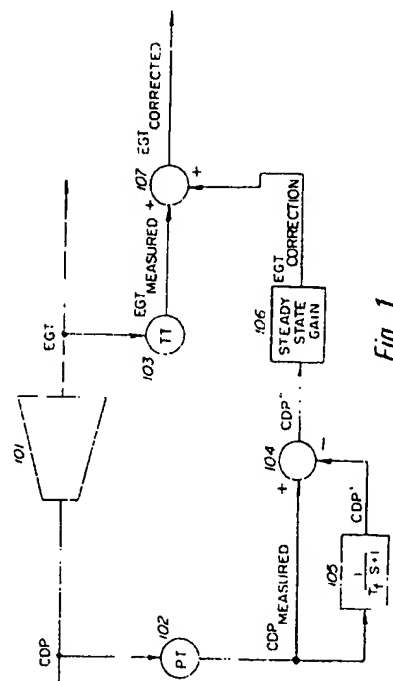
Description

This invention relates generally to a control method and apparatus for protecting gas turbines (two- and three-shaft) from damage or destruction during dangerous transients, by dynamically estimating temperatures downstream
5 of the combustion chamber, and by reducing the fuel flow rate if the estimated temperature approaches the temperature limit.

In a gas turbine the most critical temperature is located just downstream of the combustion chamber where excessive temperatures can result in damage or destruction of first-stage turbine blades. Therefore, temperatures must be limited by reducing the amount of fuel entering the combustor if the temperature becomes dangerously high. Because
10 of nonuniform distribution of the temperature-field downstream of the combustion chamber, measurement in this region is not, in general, an accurate measure of blade temperature at the inlet to the first-stage. In addition, it is difficult to have a high-speed temperature measurement near the upstream region of the first-stage inlet. This is mainly due to practicality reasons of tight volume configurations and inaccessibility near the combustion chamber sections to the first-stage inlet. Also, because of an unfriendly environment, the thermocouple transducers require shielding and pro-
15 tective thermowells which affect transducer response time and accuracy.

The present control strategy makes use of readings downstream of the gas generator turbine, where measurement is more reliable because of lower temperatures. Based on rules of thumb, testing, and empirical correlation, the exhaust temperature value at which blade damage is reached is tabulated for different operating conditions of the gas turbine. Typically, the exhaust temperature limiting value is tabulated as a function of air compressor discharge pressure (CDP).
20 In the fuel control system a safety margin is defined to keep the exhaust temperature safely below the exhaust temperature limiting value specified for a given load on the gas turbine.

As a result of the preceding compounding factors, the safety margin defined in the fuel control system (to keep the exhaust temperature at a safe value in order to prevent blade damage) is very conservative. This results in driver limitations leading to production losses, and the inability to operate the gas turbine at higher first-stage inlet tempera-
25 tures for higher operating efficiency. For the above reasons, there is a need to accurately control and regulate fuel intake during dangerous transients for two- and three-shaft gas turbines.

Solutions to the above problems are provided by the method and apparatus of the invention as specified in accompanying Claims 1, 5, 7, 11, 12, 13, 17, 19, 23 and 24. Optional features of the invention are defined in the remainder of the claims.
30 The purpose of this invention is to estimate the dynamic action of the temperature downstream of the combustion chamber of a gas turbine. This dynamic action will then be used to correct the temperatures measured by existing thermocouples. The estimate is based on the pressure of the air exiting the compressor upstream of the combustion chamber, referred to as compressor discharge pressure (CDP). CDP will be processed through a lead-lag element which results in a corrected exhaust gas temperature ($EGT_{CORRECTED}$) used by the control system to restrict fuel flow
35 during dangerous transients.

Current fuel control methods often fail to reliably measure the temperature at the most critical location - upstream of the turbine's first-stage and downstream of the combustor. Not only is this temperature difficult to measure, but it is rare to have a temperature measurement in this severe environment for turbines used in industrial applications.

An advantage of the present invention is that it uses existing thermocouples, but is less affected by inherent time
40 lags of the signal inputs. Additionally, this new control method uses the pressure of air exiting the compressor (CDP) which is easily measurable in industrial gas turbines.

This invention also offers considerable economic advantages by its method for reducing both process upset and turbine damage. Additional spin-off benefits would better ensure efficient operation, extend the intervals between scheduled shutdowns, and increase monetary savings.
45 There now follows a description of preferred embodiments of the invention, with reference to accompanying Figure 1 which shows a block diagram of the proposed control method.

To protect a process from unnecessary disruption, and to prevent damage or destruction of gas turbines (two- and three-shaft), fuel intake must not only be easily and accurately controlled, it must be restricted during dangerous transients, thereby avoiding damage to blading in the turbine's first-stage. During this operation a fuel controller reduces
50 fuel flow as needed to keep the exhaust gas temperature (EGT) below a maximum limit that is a function of compressor discharge pressure (CDP).

The control method for this invention dynamically estimates the temperature downstream of the combustor by using measurements from existing thermocouples, and by using the pressure of the air exiting the compressor (CDP) upstream of the combustor. These temperature and pressure measurements are then analyzed, resulting in a corrected
55 EGT used by the control system. Once the corrected EGT has been calculated, its first time-derivative is used to adjust the safety margin between a maximum allowable limit temperature and a lower predetermined temperature set point.

Fig. 1 depicts a block diagram of the proposed control method for a gas turbine 101 where CDP is sensed by a pressure transmitter 102 and EGT is sensed by a temperature transmitter 103. The measured EGT signal is transmitted

to a summing operation 107, whereas the measured CDP signal is transmitted simultaneously to a summing operation 104 (fast dynamics) and to a first-order lag 105 which is represented by a transfer function, $\frac{1}{T_f s + 1}$ where:

$T_f =$ time constant

5    $s =$ Laplace transform variable

Note that the first-order lag could be selected to match the dynamics between $CDP_{MEASURED}$ and $EGT_{MEASURED}$, and could be substituted by a higher-order transfer function with a pure time-delay element. CDP' is subtracted from $CDP_{MEASURED}$, and the difference, CDP" (fast dynamics of CDP), is multiplied by a steady-state gain

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$$\left[\frac{d(EGT)}{d(CDP)}\right]$$

106 to predict $EGT_{CORRECTION}$. The steady-state gain is calculated at the time of installation and is characterized as
15   a function of gas generator speed (NGG, two-shaft), or high-pressure rotor speed (NHP, three-shaft). $EGT_{CORRECTION}$ is then added to $EGT_{MEASURED}$, thereby calculating $EGT_{CORRECTED}$.

The safety margin can now be adjusted, based on the first time-derivative of $EGT_{CORRECTED}$. The EGT limit constraint is established by choosing a temperature set point at a temperature that is less than the allowable limit (initial margin of safety). Next, the corrected EGT is calculated and from its derivative value, the safety margin between the
20   maximum allowable limit temperature and the chosen temperature set point is adjusted. This instantaneous margin of safety is derived from

25

$$SM* = SM + \frac{C}{2}\left[\frac{d}{dt}(EGT_{CORRECTED}) + \left|\frac{d}{dt}(EGT_{CORRECTED})\right|\right] = SM + DR$$

where:

30    $SM* =$ instantaneous margin of safety
        $SM =$ initial margin of safety
        $DR =$ derivative response contribution to the safety margin
        $C =$ constant

35   Obviously many modifications and variations of the present invention are possible in light of the above teachings. It is, therefore, to be understood that within the scope of the appended claims, the invention may be practiced otherwise than as specifically described.

40   **Claims**

1.   A method for dynamically estimating exhaust gas temperatures downstream of a combustion chamber in a gas turbine comprising an air compressor, a combustor, means for controlling the exhaust gas temperature, and a gas generator or a high-pressure turbine, the method comprising the steps of:

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       (a) determining the air compressor's discharge pressure;
       (b) determining the gas turbine's exhaust gas temperature;
       (c) calculating a corrected exhaust gas temperature; and
       (d) regulating the control means, based on the corrected exhaust gas temperature.

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2.   The method of claim 1 wherein the steps of determining air compressor discharge pressure and gas turbine exhaust gas temperature comprise the steps of:

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       (a) sensing the compressor discharge pressure by a pressure transmitter and generating a pressure signal proportional to the compressor discharge pressure; and
       (b) sensing the exhaust gas temperature by a thermocouple and generating a temperature signal proportional to the exhaust gas temperature.

3. The method of claim 1 wherein the step of calculating a corrected exhaust gas temperature comprises the steps of:

(a) calculating a steady-state gain as a function of compressor discharge pressure and exhaust gas temperature;

(b) extracting fast dynamics from the compressor's discharge pressure signal by using a higher frequency rate than that contained in the temperature signal;

(c) multiplying the fast dynamics of the compressor discharge pressure by the steady-state gain to predict the fast dynamics of the exhaust gas temperature; and

(d) adding the predicted fast dynamics of the exhaust gas temperature to the measured exhaust gas temperature to calculate the corrected exhaust gas temperature.

4. The method of claim 3 wherein the step of extracting fast dynamics from the compressor's discharge pressure signal comprises the steps of:

(a) passing the compressor's discharge pressure signal through a lead-lag element, which represents the effects of the turbine and a measurement system on the exhaust gas temperature; and

(b) subtracting a first-order lag from the measured pressure signal to determine the fast dynamics.

5. A method of controlling a gas turbine with an exhaust gas temperature limit constraint comprising an air compressor, a combustor, means for controlling the exhaust gas temperature, and a gas generator or a high-pressure turbine, the method comprising the steps of:

(a) choosing a temperature set point at a temperature less than a maximum allowable limit;

(b) calculating a corrected exhaust gas temperature;

(c) adjusting a safety margin between the maximum allowable limit temperature and the chosen temperature set point, based on a first time-derivative of the corrected exhaust gas temperature; and

(d) changing the exhaust gas temperature in a direction toward the temperature set point if the corrected exhaust gas temper-ature is greater than the temperature set point.

6. The method of claim 5 wherein the step of adjusting a safety margin comprises the steps of:

(a) sensing changing exhaust gas temperature conditions;

(b) calculating the time-derivative of the corrected exhaust gas temperature;

(c) generating a signal proportional to the first time-derivative; and

(d) adjusting the safety margin in response to a positive derivative.

7. A method for dynamically estimating exhaust gas temperatures downstream of a combustion chamber in a gas turbine comprising an air compressor, a combustor, means for controlling the exhaust gas temperature, and a gas generator or a high-pressure turbine, the method comprising the steps of:

(a) determining the high-pressure turbine's shaft speed;

(b) determining the gas turbine's exhaust gas temperature;

(c) calculating a corrected exhaust gas temperature; and

(d) regulating the control means, based on the corrected exhaust gas temperature.

8. The method of claim 7 wherein the steps of determining turbine shaft speed and gas turbine exhaust gas temper-ature comprise the steps of:

(a) monitoring the turbine shaft speed by magnetic pickups and transmitting a frequency signal proportional to the turbine shaft speed; and

(b) sensing the exhaust gas temperature by a thermocouple and generating a temperature signal proportional to the exhaust gas temperature.

9. The method of claim 7 wherein the step of calculating a corrected exhaust gas temperature comprises the steps of:

(a) calculating a steady-state gain as a function of turbine shaft speed and exhaust gas temperature;

(b) extracting fast dynamics from the turbine's shaft speed signal by using a higher frequency rate than that contained in the temperature signal;

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(c) multiplying the fast dynamics of the turbine shaft speed by the steady-state gain to predict the fast dynamics of the exhaust gas temperature; and

(d) adding the predicted fast dynamics of the exhaust gas temperature to the measured exhaust gas temperature to calculate the corrected exhaust gas temperature.

10. The method of claim 9 wherein the step of extracting fast dynamics from the turbine's shaft speed signal comprises the steps of:

(a) passing the turbine's shaft speed signal through a lead-lag element, which represents the effects of the turbine and a measurement system on the exhaust gas temperature; and

(b) subtracting a first-order lag from the shaft speed signal to determine the fast dynamics.

11. A method for preventing thermal damage in two- and three-shaft gas turbines during dangerous transients in a gas turbine comprising an air compressor, a combustor, means for controlling the exhaust gas temperature, and a gas generator or a high-pressure turbine, the method comprising the steps of:

(a) determining the air compressor's discharge pressure;

(b) determining the gas turbine's exhaust gas temperature;

(c) choosing a temperature set point at a temperature less than a maximum allowable limit;

(d) calculating a corrected exhaust gas temperature;

(e) adjusting a safety margin between the maximum allowable limit temperature and the chosen temperature set point, based on a first time-derivative of the corrected exhaust gas temperature;

(f) reducing the safety margin to a minimum, based on a ramp rate;

(g) maintaining the safety margin within control limits; and

(h) modulating a fuel flow in response to the value of the corrected exhaust gas temperatures.

12. A method for preventing thermal damage in two- and three-shaft gas turbines during dangerous transients in a gas turbine comprising an air compressor, a combustor, means for controlling the exhaust gas temperature, and a gas generator or a high-pressure turbine, the method comprising the steps of:

(a) determining the high-pressure turbine's shaft speed;

(b) determining the gas turbine's exhaust gas temperature;

(c) choosing a temperature set point at a temperature less than the maximum allowable limit;

(d) calculating a corrected exhaust gas temperature;

(e) adjusting a safety margin between the maximum allowable limit temperature and the chosen temperature set point, based on a first time-derivative of the corrected exhaust gas temperature;

(f) reducing the safety margin to a minimum, based on a ramp rate;

(g) maintaining the safety margin within control limits; and

(h) modulating a fuel flow in response to the value of the corrected exhaust gas temperatures.

13. An apparatus for dynamically estimating exhaust gas temperatures downstream of a combustion chamber in a gas turbine comprising an air compressor, a combustor, means for controlling the exhaust gas temperature, and a gas generator or a high-pressure turbine, the apparatus comprising:

(a) means for determining the air compressor's discharge pressure;

(b) means for determining the gas turbine's exhaust gas temperature;

(c) means for calculating a corrected exhaust gas temperature; and

(d) means for regulating the control means, based on the corrected exhaust gas temperature.

14. The apparatus of claim 13 wherein the steps of determining air compressor discharge pressure and gas turbine exhaust gas temperature comprise:

(a) means for sensing the compressor discharge pressure by a pressure transmitter and generating a pressure signal proportional to the compressor discharge pressure; and

(b) means for sensing the exhaust gas temperature by a thermocouple and generating a temperature signal proportional to the exhaust gas temperature.

15. The apparatus of claim 13 wherein the step of calculating a corrected exhaust gas temperature comprises:

(a) means for calculating a steady-state gain as a function of compressor discharge pressure and exhaust gas temperature;

(b) means for extracting fast dynamics from the compressor's discharge pressure signal, said extracting means having a higher frequency rate than that contained in the temperature signal;

(c) means for multiplying the fast dynamics of the compressor discharge pressure by the steady-state gain to predict the fast dynamics of the exhaust gas temperature; and

(d) means for adding the predicted fast dynamics of the exhaust gas temperature to the measured exhaust gas temperature to calculate the corrected exhaust gas temperature.

16. The apparatus of claim 15 wherein the step of extracting fast dynamics from the compressor's discharge pressure signal comprises:

(a) means for passing the compressor's discharge pressure signal through a lead-lag element, which represents the effects of the turbine and a measurement system on the exhaust gas temperature; and

(b) means for subtracting a first-order lag from the measured pressure signal to determine the fast dynamics.

17. An apparatus for controlling a gas turbine with an exhaust gas temperature limit constraint comprising an air compressor, a combustor, means for controlling the exhaust gas temperature, and a gas generator or a high-pressure turbine, the apparatus comprising:

(a) means for choosing a temperature set point at a temperature less than a maximum allowable limit;

(b) means for calculating a corrected exhaust gas temperature;

(c) means for adjusting a safety margin between the maximum allowable limit temperature and the chosen temperature set point, based on a first time-derivative of the corrected exhaust gas temperature; and

(d) means for changing the exhaust gas temperature in a direction toward the temperature set point if the corrected exhaust gas temperature is greater than the temperature set point.

18. The apparatus of claim 17 wherein the step of adjusting a safety margin comprises:

(a) means for sensing changing exhaust gas temperature conditions;

(b) means for calculating the time-derivative of the corrected exhaust gas temperature;

(c) means for generating a signal proportional to the first time-derivative; and

(d) means for adjusting the safety margin in response to a positive derivative.

19. An apparatus for dynamically estimating exhaust gas temperatures downstream of a combustion chamber in a gas turbine comprising an air compressor, a combustor, means for controlling the exhaust gas temperature, and a gas generator or a high-pressure turbine, the apparatus comprising:

(a) means for determining the high-pressure turbine's shaft speed;

(b) means for determining the gas turbine's exhaust gas temperare;

(c) means for calculating a corrected exhaust gas temperature; and

(d) means for regulating the control means, based on the corrected exhaust gas temperature.

20. The apparatus of claim 19 wherein the steps of determining turbine shaft speed and gas turbine exhaust gas temperature comprise:

(a) means for monitoring the turbine shaft speed by magnetic pickups and transmitting a frequency signal proportional to the turbine shaft speed; and

(b) means for sensing the exhaust gas temperature by a thermocouple and generating a temperature signal proportional to the exhaust gas temperature.

21. The apparatus of claim 19 wherein the step of calculating a corrected exhaust gas temperature comprises:

(a) means for calculating a steady-state gain as a function of turbine shaft speed and exhaust gas temperature;

(b) means for extracting fast dynamics from the turbine's shaft speed signal, said extracting means having a higher frequency rate than that contained in the temperature signal;

(c) means for multiplying the fast dynamics of the turbine shaft speed by the steady-state gain to predict the fast dynamics of the exhaust gas temperature; and

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(d) means for adding the predicted fast dynamics of the exhaust gas temperature to the measured exhaust gas temperature to calculate the corrected exhaust gas temperature.

22. The apparatus of claim 21 wherein the step of extracting fast dynamics from the turbine's shaft speed signal comprises:

    (a) means for passing the turbine's shaft speed signal through a lead-lag element, which represents the effects of the turbine and a measurement system on the exhaust gas temperature; and
    (b) means for subtracting a first-order lag from the shaft speed signal to determine the fast dynamics.

23. An apparatus for preventing thermal damage in two- and three-shaft gas turbines during dangerous transients in a gas turbine comprising an air compressor, a combustor, means for controlling the exhaust gas temperature, and a gas generator or a high-pressure turbine, the apparatus comprising:

    (a) means for determining the air compressor's discharge pressure;
    (b) means for determining the gas turbine's exhaust gas temperature;
    (c) means for choosing a temperature set point at a temperature less than a maximum allowable limit;
    (d) means for calculating a corrected exhaust gas temperature;
    (e) means for adjusting a safety margin between the maximum allowable limit temperature and the chosen temperature set point, based on a first time-derivative of the corrected exhaust gas temperature;
    (f) means for reducing the safety margin to a minimum, based on a ramp rate;
    (g) means for maintaining the safety margin within control limits; and
    (h) means for modulating a fuel flow in response to the value of the corrected exhaust gas temperatures.

24. An apparatus for preventing thermal damage in two- and three-shaft gas turbines during dangerous transients in a gas turbine comprising an air compressor, a combustor, means for controlling the exhaust gas temperature, and a gas generator or a high-pressure turbine, the apparatus comprising:

    (a) means for determining the high-pressure turbine's shaft speed;
    (b) means for determining the gas turbine's exhaust gas temperature;
    (c) means for choosing a temperature set point at a temperature less than a maximum allowable limit;
    (d) means for calculating a corrected exhaust gas temperature;
    (e) means for adjusting a safety margin between the maximum allowable limit temperature and the chosen temperature set point, based on a first time-derivative of the corrected exhaust gas temperature;
    (f) means for reducing the safety margin to a minimum, based on a ramp rate;
    (g) means for maintaining the safety margin within control limits; and
    (h) means for modulating a fuel flow in response to the value of the corrected exhaust gas temperatures.
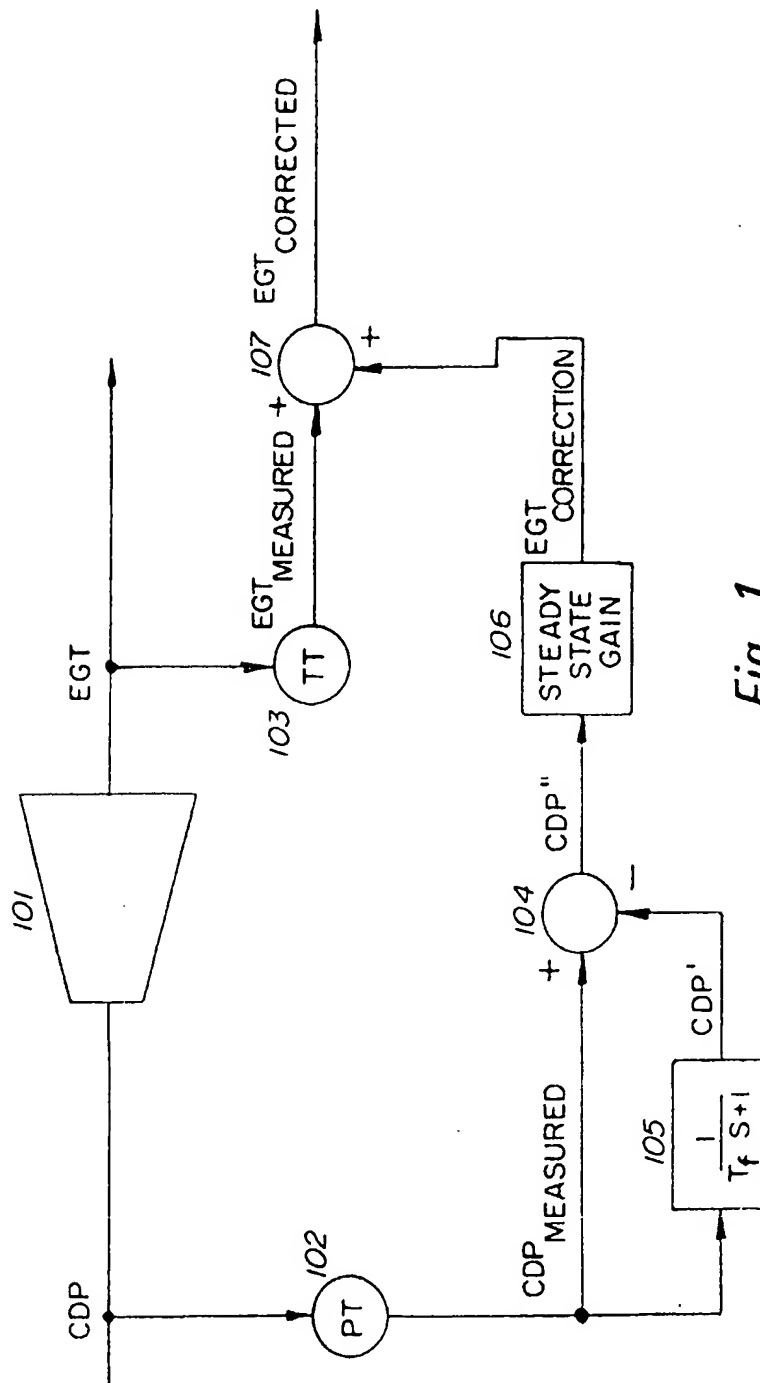
Fig. 1

<table>
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Office</td><td>EUROPEAN SEARCH REPORT</td><td>Application Number
EP 96 30 0839</td></tr>
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DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
X	US-A-4 055 997 (KNIAT JOHN) 1 November 1977 * the whole document * ---	1,2,5, 11,13, 14,17,23	F02C9/28 F02C9/00
X	GB-A-2 011 091 (GEN ELECTRIC) 4 July 1979	1,2,5, 11,13, 14,17,23	
A	* the whole document * ---	3,4,6, 15,16,18	
X	CH-A-649 606 (HITACHI LTD) 31 May 1985 * the whole document * ---	1-24	
A	US-A-3 956 883 (ANDERSON JOEL M ET AL) 18 May 1976 * the whole document * ---	1-24	
X	US-A-4 307 451 (ZAGRANSKI RAYMOND D ET AL) 22 December 1981 * the whole document * ---	7-10,12, 19-22	
A	US-A-5 212 943 (HARRIS JAMES J) 25 May 1993 * the whole document * ---	1-24	TECHNICAL FIELDS SEARCHED (Int.Cl.6) F02C
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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	5 June 1996	Iverus, D

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DOCUMENTS CONSIDERED TO BE RELEVANT

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A	US-A-2 809 492 (ARKAWY) 15 October 1957 ---		
A	US-A-3 789 665 (HOHENBERG R) 5 February 1974 -----		
			TECHNICAL FIELDS SEARCHED (Int.Cl.6)

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